

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank) 2. REPORT DATE November, 1994 3. REPORT TYPE AND DATES COVERED Final Report Nov. 1, 1991-Oct. 31, 1994

4. TITLE AND SUBTITLE
Tropical Cyclone Propagation

5. FUNDING NUMBERS
G: N00014-91-J-1092

6. AUTHOR(S)
William M. Gray

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
William M. Gray
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Yolanda M. Medina Univ. of New Mexico
Procurement Technician Bandelier Hall West
Depart of the Navy Albuquerque NM 87131
Office of Naval Research

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT R
Approved for public release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) This paper discusses the question of tropical cyclone propagation or why the average tropical cyclone moves 1-2 m/s faster and usually 10-20° to the left of its surrounding (or 5-7° radius) deep layer (850-300 mb) steering current. It is shown that the primary factor causing tropical cyclones to propagate faster and to the left of their steering flow is their location within a baroclinic environment. Irrespective of direction to which it moves or of the latitude it exists, the tropical cyclone has an environment of warm tropospheric air on its right side and cold tropospheric air on its left side. The vertical wind shear and the slope to cold air resulting from this baroclinic environment lead to a reduction in the component of surrounding wind in the direction of cyclone movement. Hydrostatics dictate that the vertical slope of anticyclones, monsoon troughs, and frontal systems be towards the cold air side. The faster movement of the cyclone center creates a forward minus rear wind asymmetry which in turn causes the inner cyclone circulation to move 10-20° to the left of the broader steering current flow.

14. SUBJECT TERMS

15. NUMBER OF PAGES
36 pp.

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

18. SECURITY CLASSIFICATION
OF THIS PAGE

19. SECURITY CLASSIFICATION
OF ABSTRACT

20. LIMITATION OF ABSTRACT



DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
SEATTLE REGIONAL OFFICE
1107 NE 45TH STREET, SUITE 350
SEATTLE WA 98105-4631

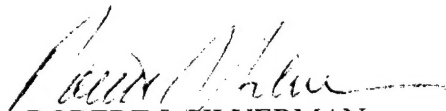
IN REPLY REFER TO:

4330
ONR 247
11 Jul 97

From: Director, Office of Naval Research, Seattle Regional Office, 1107 NE 45th St., Suite 350, Seattle, WA 98105
To: Defense Technical Center, Attn: P. Mawby, 8725 John J. Kingman Rd., Suite 0944, Ft. Belvoir, VA 22060-6218

Subj: RETURNED GRANTEE/CONTRACTOR TECHNICAL REPORTS

1. This confirms our conversations of 27 Feb 97 and 11 Jul 97. Enclosed are a number of technical reports which were returned to our agency for lack of clear distribution availability statement. This confirms that all reports are unclassified and are "APPROVED FOR PUBLIC RELEASE" with no restrictions.
2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.


ROBERT J. SILVERMAN

FINAL REPORT
TROPICAL CYCLONE PROPAGATION

19970717 125

W. M. Gray,

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

November, 1994

ABSTRACT

This paper discusses the question of tropical cyclone propagation or why the average tropical cyclone moves 1-2 m/s faster and usually 10-20° to the left of its surrounding (or 5-7° radius) deep layer (850-300 mb) steering current. It is shown that the primary factor causing tropical cyclones to propagate faster and to the left of their steering flow is their location within a baroclinic environment. Irrespective of direction to which it moves or of the latitude it exists, the tropical cyclone has an environment of warm tropospheric air on its right side and cold tropospheric air on its left side. The vertical wind shear and the slope to cold air resulting from this baroclinic environment lead to a reduction in the component of surrounding wind in the direction of cyclone movement. Hydrostatics dictate that the vertical slope of anticyclones, monsoon troughs, and frontal systems be towards the cold air side. The faster movement of the cyclone center creates a forward (faster) minus rear (slower) wind asymmetry which in turn causes the inner cyclone circulation to move 10-20° to the left of the broader steering current flow.

The typical cyclone's pressure-wind adjustments to Beta influences induces asymmetric wind convergence (west side) and divergence (east side) about the cyclone. These asymmetric divergence patterns result in large asymmetric variations of the tropical cyclone's deep convection and of its tangential wind. Asymmetric deep convection produces a vorticity change and cyclone propagation in directions different (i.e., to the south) from that specified by barotropic northwesterly Beta drift. Such wind and convective asymmetries act to negate much of northwesterly Beta propagation effect obtained in one level model simulation. Hence, the primary factor to the understanding of tropical cyclone propagation rests with an appreciation of the fundamental role of the baroclinic environment in which the tropical cyclone is embedded.

1 INTRODUCTION

This paper discusses tropical cyclone (TC) propagation which is defined as the difference between movement of the TC and its outer radius deep layer steering current. Previous analyses

have shown that the 5-7° radius 850-300 mb layer mean flow give a reasonably good representation of the tropical cyclone's steering environment (Chan and Gray, 1982; Gray *et al.*, 1988).

The author has made many new TC motion related rawinsonde composite analyses for north-west Pacific, Atlantic, and the Australia-South Pacific tropical cyclones. Composite data have been stratified by three motion direction categories (west, north, and northeast) and three speed (slow, average, and fast) categories. Stratification has also been made for stationary or nearly stationary cyclones in each basin and for cyclones with stronger or weaker outer environmental flow. Special software programs have been developed to calculate the surrounding cyclone deep layer wind components parallel and perpendicular to the fixed and moving cyclone center. The primary purpose of these analyses has been to quantitatively document the relationship between the tropical cyclone's center motion and its surrounding deep layer (850-300 mb) winds at various radii. These composited data sets show that:

1. Tropical cyclones move with a speed and direction very close to their interior, 1-3° radius tropospheric mean wind currents. There is little propagation component of the cyclone center motion relative to this deep layer interior current.
2. There are systematic and progressive differences between TC motion and the average 850-300 mb outer radius winds at 3-5°, 5-7°, 7-9° and 9-11° radius. Tropical cyclones move systematically and progressively faster and to the left ¹ (for N. Hemisphere orientation) of their outer radius deep layer mean flow as one moves closer to the center.

Figure 1 illustrates how the tropical cyclone's center and the mean winds at 2° and 4° radius move systematically faster and to the left of the outer 6° and 8° radii winds. This is true for nearly all of our speed and direction rawinsonde motion stratifications. Westerly, northerly and northeasterly moving tropical cyclones are all observed to have roughly the same 6° and 8° speed

¹Westward moving Atlantic cyclones move slightly to the right of their deep layer steering current because of special Atlantic environmental conditions associated with the lack of a monsoon trough).

and direction orientations in relation to their interior 2° and 4° wind vectors. (See Appendix, Fig. A1).

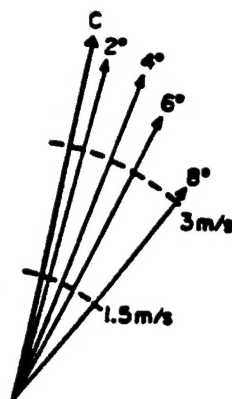


Figure 1: Synthesis of the TC motion vector (C) relative to the 850-300 mb mean wind in the 2° (1-3°), 4° (3-5°), 6° (5-7°) and 8° radial belts.

There is no question that tropical cyclones always move faster and almost always to the left (except for westward moving Atlantic cyclone which exist in a non-monsoon environment) of their $5-7^\circ$ radius 300-850 mb mean deep layer surrounding flow. Why should tropical cyclones display such a consistent propagation component irrespective of cyclone speed, direction, or ocean basin? This paper attempts to answer this question.

1.1 Barotropic Modeling

A fundamental theme in recent theoretical TC motion research has been to explain the physical processes responsible for causing tropical cyclones to have a propagation component relative to their surrounding deep layer environmental steering currents. A major methodological approach for attempting to better understand TC propagation has involved barotropic modeling on a Beta plane. Barotropic numerical modeling efforts of the last few years have been carried on by a number of researchers [Holland (1983); DeMaria (1985, 1987); Chan and Williams (1987); Willoughby (1988); Smith (1989); Fiorino and Elsberry (1989); Evans *et. al.* (1990); Carr (1989); Carr and

Elsberry (1989); and others]. Although there are some differences between the various barotropic simulations and their interpretations, there has been a general unity of view that one level Beta drift is a dominant influence on cyclone propagation. This may be a correct interpretation as regards one-level model simulation but may not be very representative of the real-world propagation for tropical cyclones which exist within a baroclinic atmosphere where Beta-induced influences in baroclinic simulations can produce other likely propagation influences. Vertical varying influences may act to partially cancel some of the propagation responses inherent in the barotropic simulations.

Other one-level numerical model runs have been run with the added influence of horizontal gradients of relative vorticity (De Maria, 1985, 1987). It has been found that one layer vortex propagation can also be significantly influenced by the varying horizontal gradients of relative vorticity in which the cyclone might exist. But a generalization of this to actual cases of tropical cyclone motion has yet to be accomplished.

It is likely that these many barotropic propagation simulations have neglected certain essential processes that may play a primary role in real-world tropical cyclone propagation. This assertion should be given consideration, particularly if the results of such barotropic simulations are not well substantiated in the observations. For example, our rawinsonde compositing studies of stalled and slowly moving ($< 3\text{ms}^{-1}$) tropical cyclones in the NW Pacific and Atlantic basins show no obvious northwest propagation of the tropical cyclone center relative to the ambient surrounding 850-300 mb mean wind flow. (See Appendix, Fig. A2). We also find no evidence that the inner-radii winds of eastward moving tropical cyclones move slower than outer radii winds as Beta-drift theory would imply. Eastward moving cyclones and inner radius deep layer flows are observed to track as fast or faster than their surrounding outer radius flows. (See Appendix, Fig. A1). Such inconsistency with Beta-drift theory for eastward moving cyclones cannot be explained by differences in the gradients of relative vorticity between east versus west tracking cyclones as some researchers have suggested. Observations do not support large differences in the relative orientations of the gradients of relative vorticity for eastward versus westward moving cyclones. We also do not

observe that typhoons and hurricanes with very strong outer radii tangential circulations possess larger forward and more leftward propagation components than cyclones with substantially weaker outer circulations as implied by the barotropic simulations of Chan and Williams, 1987. Rather, we observe that propagation is very similar for cyclones with outer circulations of different strength as it is for cyclones moving in different directions. Propagation appears to be to a large extent independent of cyclone structure and of cyclone direction of motion. This is not to say that Beta influences are not an important component of cyclone propagation but, as will be discussed, Beta influences can be understood only in a baroclinic context.

The author does not question the validity of any of the barotropic propagation simulations only their applicability to real world TC propagation. It is likely that because of the special baroclinic environment in which the TC exists and because of the extra Beta influences on baroclinic dynamics, cyclone propagation related factors are in operation which are significantly different from those specified by one-level dynamics.

The added complexity of environmental baroclinicity and divergence processes on cyclone propagation have yet to be well sorted out in either an observational, theoretical, or numerical modeling context. This paper proposes a new approach to the interpretation of TC propagation. I will attempt to explain real world tropical cyclone propagation as primarily a consequence of processes associated with the existence of the TC vortex within its peculiar baroclinic environment.

2 HYPOTHESIS

The author hypothesizes that TCs move faster than their outer radii deep layer flow because of the baroclinic character of the environmental current in which the moving tropical cyclones exist. When viewed looking in the direction of cyclone movement, it is observed that the cyclone's tropospheric environment has warm air on the right side and cold air on the left side throughout the deep layer flow. This baroclinic steering environment causes an upward and leftward slope of the cyclone's surrounding environmental flow features. All moving tropical cyclones, irrespective

of direction exist in a tropospheric environment having right side (warm) to left side (cool) baroclinicity. These environmental baroclinic influences cause a leftward vertical slope of the monsoon trough or the frontal system near where the tropical cyclone forms or exists. It also causes a similar leftward upper slope of the subtropical ridge on the tropical cyclone's right side.

It is well known that tropospheric troughs and ridges slope with height to their cold air sides. This typical leftward upward slope of the cyclone's environmental flow features for westward and northward moving cyclones is shown in Fig. 2. A similar slope occurs for northeast moving cyclones. In the upper diagram the cyclone center is located at the warmest location and has no vertical shear of environmental wind around its center. To the north (or the right side of the top diagram) the environmental trade winds weaken with height and westerlies are present in the upper troposphere. To the left or south side, environmental wind shears are opposite to those on the right side. Low level winds are weak but increase with height to become strongly easterly in the upper troposphere. Note the north to south upward vertical slope of the subtropical ridge. Note also a similar north to south (or right to left) upward slope of the monsoon trough.

The bottom diagram of Fig. 2 is analogous to the top panel but for northward moving cyclones. It shows a similar leftward or to the west upward vertical slope of the cyclone's surrounding environmental wind patterns. The subtropical ridge to the right side slopes with height toward the cyclone, the trough or frontal system to the left side slopes with height to the cold air on its left. A very similar type of environmental slope occurs for those tropical cyclones moving northeastward (not shown). The typical left to right side horizontal shear of the environmental wind in the direction of the cyclone and relative to the cyclone center motion (i.e., MOTROT² minus VORT³ coordinate, see Gray *et al.*, 1988) at 850 mb and 200 mb and the shear between these layers is shown in Fig. 3.

²Wind data are in a storm MOTion relative coordinate system wherein data have also been ROTated to a common heading oriented in the direction of storm motion; hence MOTROT (see Gray, *et al.*, 1988).

³The mean symmetrical wind speeds around the cyclone; hence, the storm VORTex or VORT.

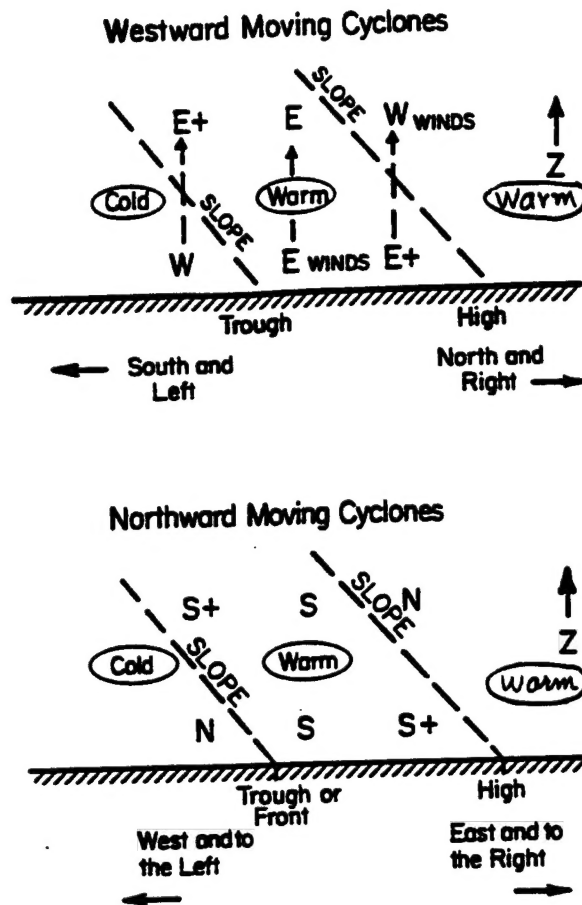


Figure 2: Vertical cross section of the tropical cyclone's typical environmental wind components parallel to its motion for northeast moving cyclones (top diagram), northward moving (middle diagram) and westward moving (at bottom). E, W, N, S stand for the direction from which the environmental wind is blowing. The cyclone is located at the warm designation.

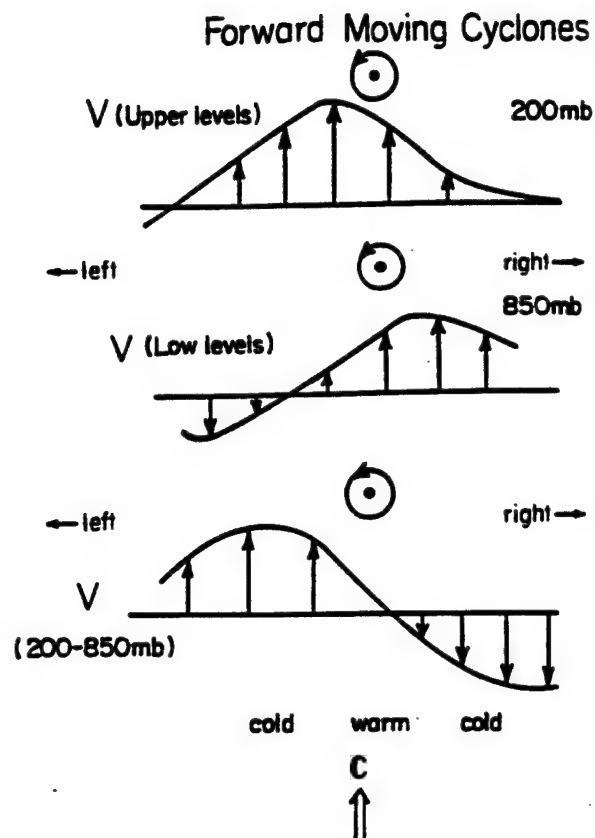


Figure 3: Portrayal of typical left to right side horizontal shear of environmental wind in the direction of the cyclone and relative to the cyclone center motion (MOTROT minus VORT. coordinate). Note the change of the sign of the 200-850 mb vertical across the cyclone center.

There is thus a general similarity of the vertical variations of the moving cyclone's right to left environmental wind fields, regardless of the cyclone's direction of motion. These typical vertical slopes of surrounding wind fields can be idealized as in Fig. 4. Typical vortex subtracted and rotated environmental wind velocities parallel to the cyclone's motion are shown. In this case, the cyclone is moving at 3 units of environmental velocity. Note that at the location of the cyclone center there can be no vertical wind shear. Environmental 850 mb and 200 mb pressure-height lines show the characteristic leftward upper slope of the environmental flow conditions. These typical pressure-height slopes cause the vertical variations of the parallel environmental winds which are shown. The parallel component of the environmental wind on the right side decreases with height from 4 to 1 units. The environmental parallel wind component on the left side increases from 1 unit at the lower level to 4 units at upper levels. Note that such environmental flow conditions would exist irrespective of whether a tropical cyclone were present or not.

It is these vertical changes in the cyclone's surrounding environmental parallel wind components which are responsible for the cyclone's characteristic faster than environmental motion and its general propagation component. Cyclones move faster than their environmental flow because the deep layer mean environmental winds on their right and left sides are slower than the deep layer environmental winds which blow across the cyclone's center. Figure 5 is similar to Fig. 4. It shows the corresponding environmental mean tropospheric wind conditions associated with the flow fields of Fig. 4. Note in Fig. 5 that the mean parallel component of the two level winds near the cyclone center is 3 units while the two level or deep layer parallel components to the right and left sides are but $2\frac{1}{2}$ (i.e., one-half of 4 plus 1 units) or $\frac{1}{2}$ unit less than at the center. This results in forward propagation.

3 ENVIRONMENTAL HEIGHT GRADIENTS ACROSS THE CYCLONE

Verification that the cyclone's broad scale right to left side environment is baroclinic with warm air to the right of the cyclone and cold air to the left can be substantiated by an analysis of

Slope to the Left with Height

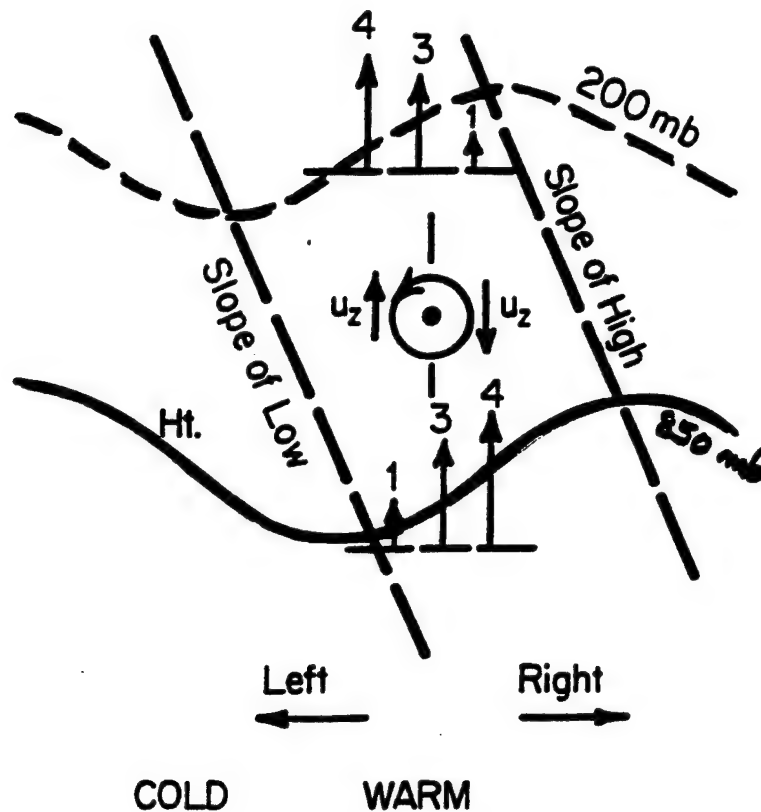


Figure 4: Idealized vertical cross section of the typical slope of the tropical cyclone's left to right environmental 850 mb and 200 mb height fields with associated idealized environmental wind components parallel to the cyclone motion. Cyclone winds are not included. The cyclone and the winds are directed into the paper. This typical picture is valid for all cyclone direction orientations.

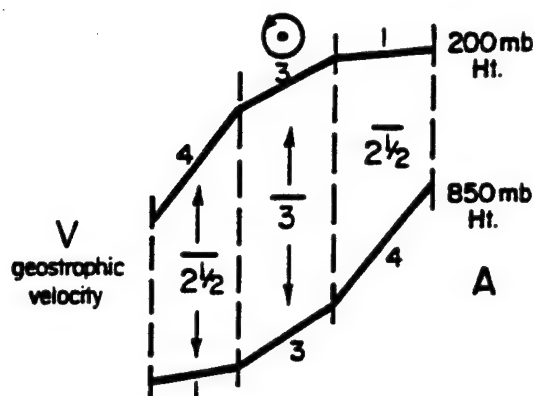


Figure 5: Idealized cross section of the typical slope of the 200 and 850 mb environmental height field to the right and left of a moving cyclone with the resulting deep layer mean parallel component of the gradient winds. 850 and 200 mb level averages 3 units around the cyclone center but only $2\frac{1}{2}$ units (half of $4 + 1$) to the right and left of the cyclone.

the right to left side tropospheric thickness patterns. Figure 6 is typical. Note the higher 850-300 mb thickness values on the right side and the generally lower thickness values to the left side. All of our westward, northward and northeast rawinsonde composites show such characteristic deep layer right versus left side thickness differences.

Figure 7 gives a plan view idealization of the deep layer left to right environmental temperature gradient across the tropical cyclone. This environmental temperature gradient is superimposed and combined upon the temperature gradient of the cyclone. Figure 8 shows that this idealized left to right side temperature gradient is present irrespective of cyclone direction of motion.

4 RIGHT AND LEFT QUADRANT WIND FIELDS ACROSS THE TROPICAL CYCLONE

The strength of the parallel component of the cyclone's right and left side winds relative to the moving cyclone center is a primary component of cyclone propagation. The top diagram of Fig. 9 portrays such typical MOTROT tangential (V_T) winds parallel to the cyclone motion at 850 mb and 200 mb. Note the reversal of vertical shear. If the symmetric component of vortex motion were to be subtracted from these winds or these winds portrayed in the MOTROT-VORT coordinate

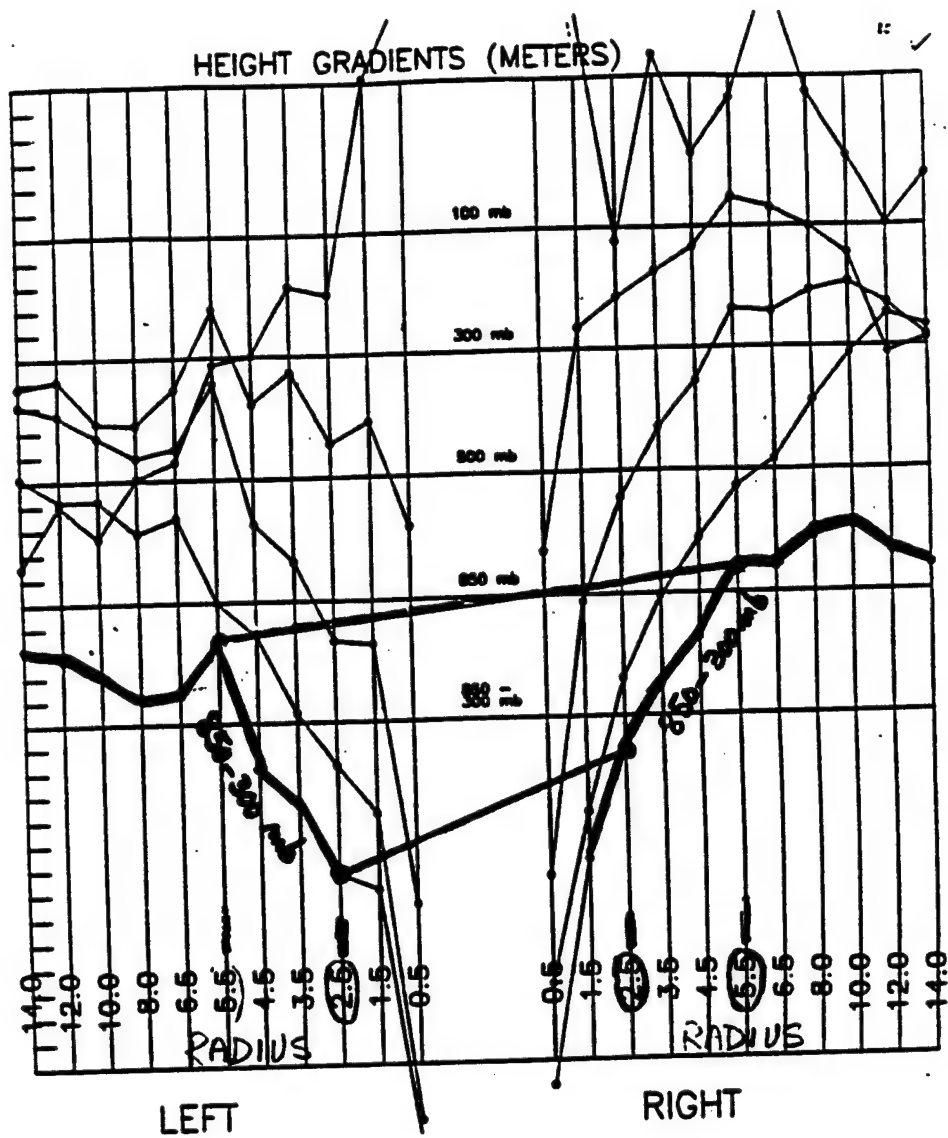


Figure 6: Rawinsonde composite right versus left side pressure-height differences for a West Pacific WNW moving cyclone in the speed range of 4-6 m/s. Small tick marks equal 5m.

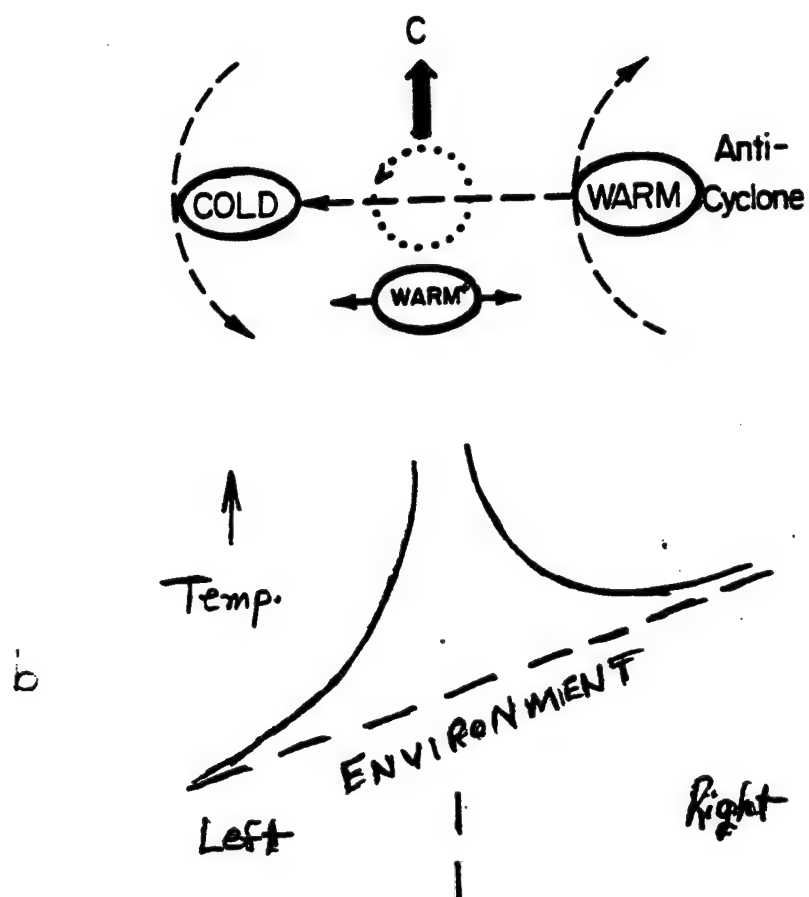


Figure 7: Plan view of right quadrant (warm) to left quadrant (cold) environmental temperature gradient superimposed across the warm central cyclone (top diagram). Bottom diagram shows the idealized left to right side combined environment and cyclone tropospheric temperature gradient.

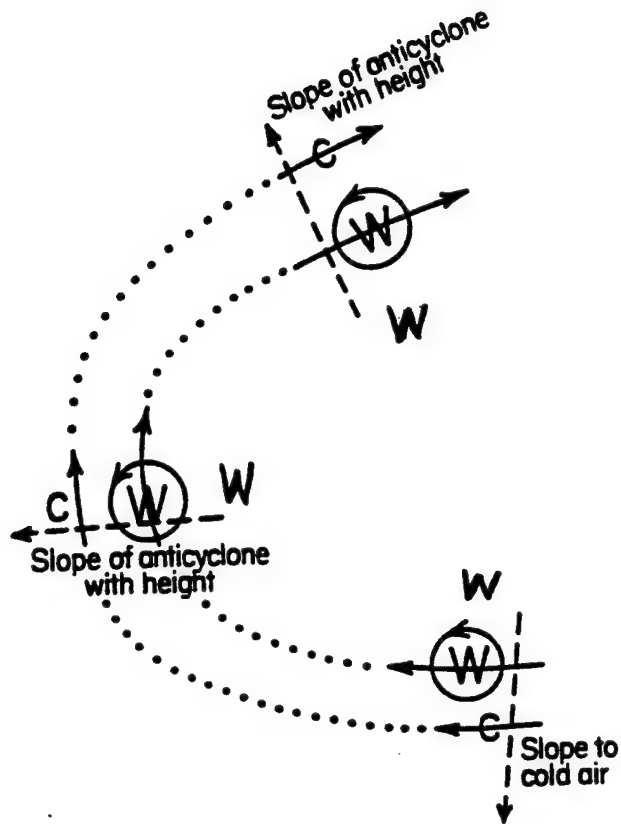


Figure 8: Idealized portrayal of how an environmental warm to cold temperature gradient is present across the cyclone from right to left, irrespective of cyclone direction of motion.

system a better understanding of forward propagation can be obtained (bottom diagram). Observe how the outer radius or the 5-7° radius average of the 200 mb and 850 mb winds in the MOTROT-VORT system is negative. Outer radius winds in the direction of motion are weaker.

5 LAPNACIAN OF THE WIND SHEAR

Tropical cyclones thus move faster than their environmental 4°, 6°, or 8° radial winds because of the character of the baroclinic environment in which the cyclone vortex is embedded. One does not have to resort to Beta-drift arguments to explain such forward propagation. The character of the horizontal wind shear across the vortex at 850 mb and 200 mb is now examined. Real-world vortices exhibit a characteristic shear as shown in the top diagram of Fig. 11. The cyclone's vortex exists on the right side of the maximum low level horizontal shear of the parallel component of the environment (V) in the direction of cyclone motion. If x is taken from left to right across the vortex, then 850 mb $\frac{\partial^2 V}{\partial x^2}$ is negative. At 200 mb the maximum left to right horizontal wind shear is to the right side of the vortex but $\frac{\partial^2 V}{\partial x^2}$ is still negative. The top diagram of Fig. 11 and the conditions shown in Fig. 12 portray these typical horizontal wind shear conditions which are observed and which are largely independent of cyclone direction of motion.

Table 1 shows the rawinsonde derived right minus left quadrant parallel component of the mean environmental winds in the direction of cyclone motion where the mean cyclone vortex winds have been subtracted out of each wind. This table shows the mean values for all west, north, and northeast moving cyclones in the NW Pacific and the Atlantic. Individual composites differing in cyclone direction, speed and ocean basin values give similar values. Inspection of Fig. 12 shows that $\frac{\partial^2 V}{\partial x^2}$ at 200 mb and $\frac{\partial^2 V}{\partial x^2}$ at 850 mb are always observed to be negative for all moving cyclone directions.

The speed of forward propagation (P_F) of the cyclone vortex relative to its mean tropospheric 5-7° radius 850-300 mb average wind can be approximated as:

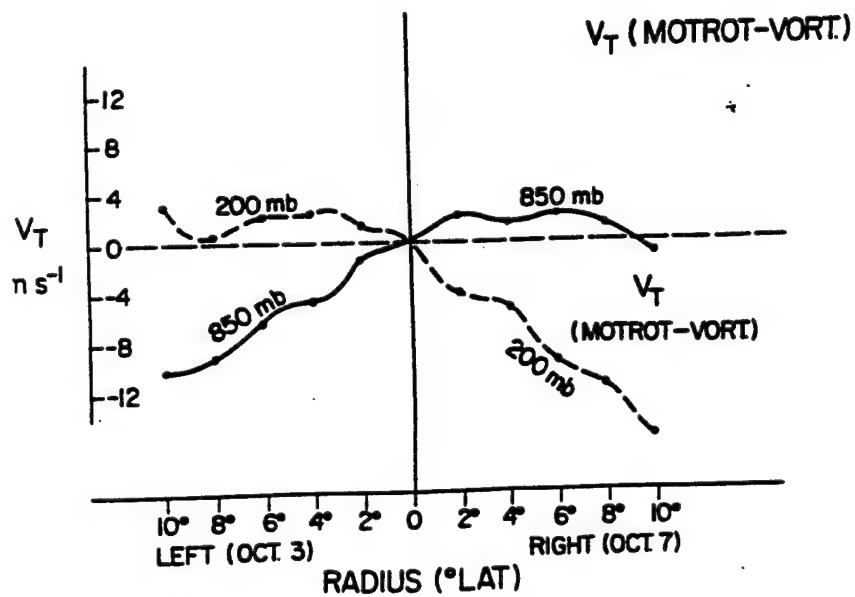
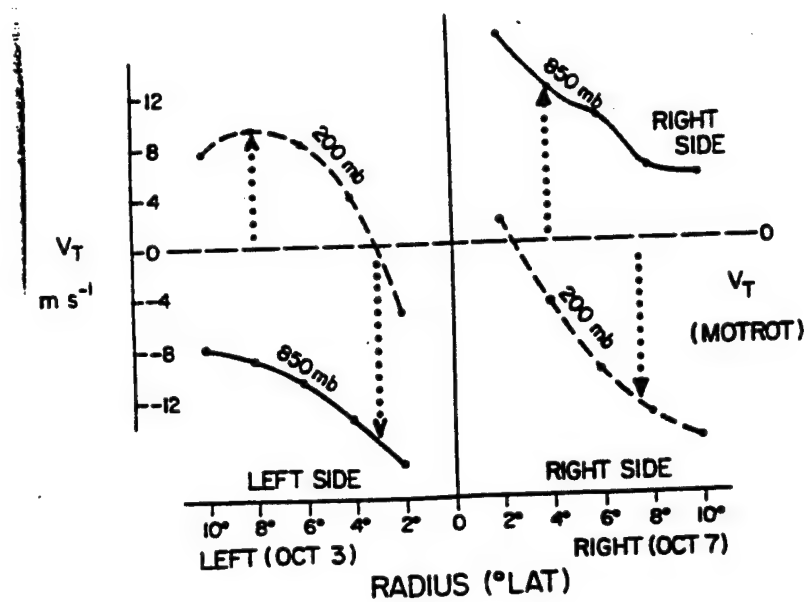


Figure 9: Portrayal of typical right versus left tangential wind components at 850 mb and 200 mb in the MOTROT coordinate system (top diagram) and in the MOTROT-VORT system (bottom diagram).

BAROCLINIC GYRE

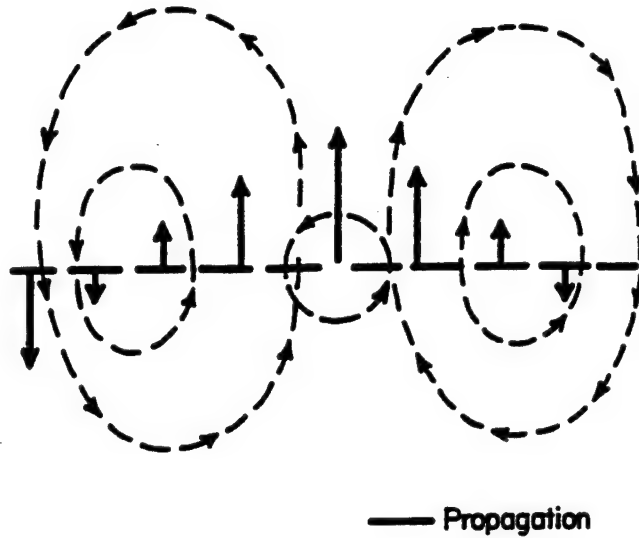


Figure 10: Idealized portrayal of the left to right side parallel component of the deep layer MOTROT minus VORT environmental wind about the tropical cyclone. Strongest deep-layer wind are at the cyclone center as representative of a baroclinic gyre.

$$P_F = -K \left[\frac{\partial^2 V}{\partial x^2} \right]_{200mb} + \frac{\partial^2 V}{\partial x^2} \Big|_{850mb} \quad (1)$$

where

K is an empirically determined constant equal to
about 3×10^5 m for deep layer horizontal shear
determination between 6° radius to the right and left.

Substitution of observational values into Eq. 1 gives forward propagation values of about 1-3 m/s relative to the $5-7^\circ$ mean tropospheric wind which matches observations. If, by contrast, the right to left side environmental shear patterns were to be arranged oppositely as indicated on the bottom diagram of Fig. 11, then the right hand side of Eq. 1 would be negative and the environmental tropospheric flow near the cyclone center would be slower than the surrounding $5-7^\circ$ mean tropospheric winds. A backward or negative cyclone propagation would then occur and require a right to left environmental temperature gradient, opposite from that which is observed.

If the $\frac{\partial^2 V}{\partial x^2}$ of the horizontal shears at both levels across the cyclone were zero, then so too would be forward propagation.

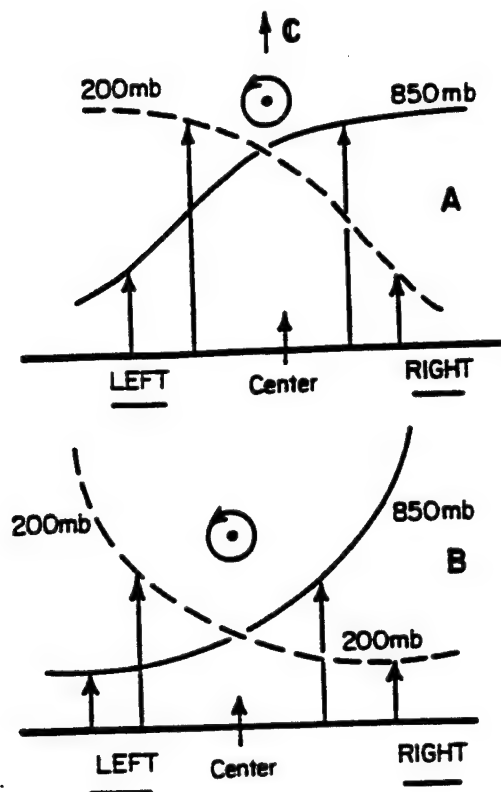


Figure 11: Contrast of opposite types of left to right environmental wind parallel to the direction of cyclone motion at 850 and 200 mb. Diagram A is for conditions as they are observed and for which forward cyclone propagation results. Diagram B shows opposite horizontal shear patterns which would, if such shearing conditions existed, lead to negative or backward propagation. Diagram B conditions are not observed, however.

5.1 Cyclone Leftward Propagation

Except for westward moving cyclones in the Atlantic, which as noted previously have special environmental conditions, all of our rawinsonde composite stratifications show a consistent movement of the tropical cyclone's inner core 1-3° radius deep layer mean wind 10 to 25° to the left

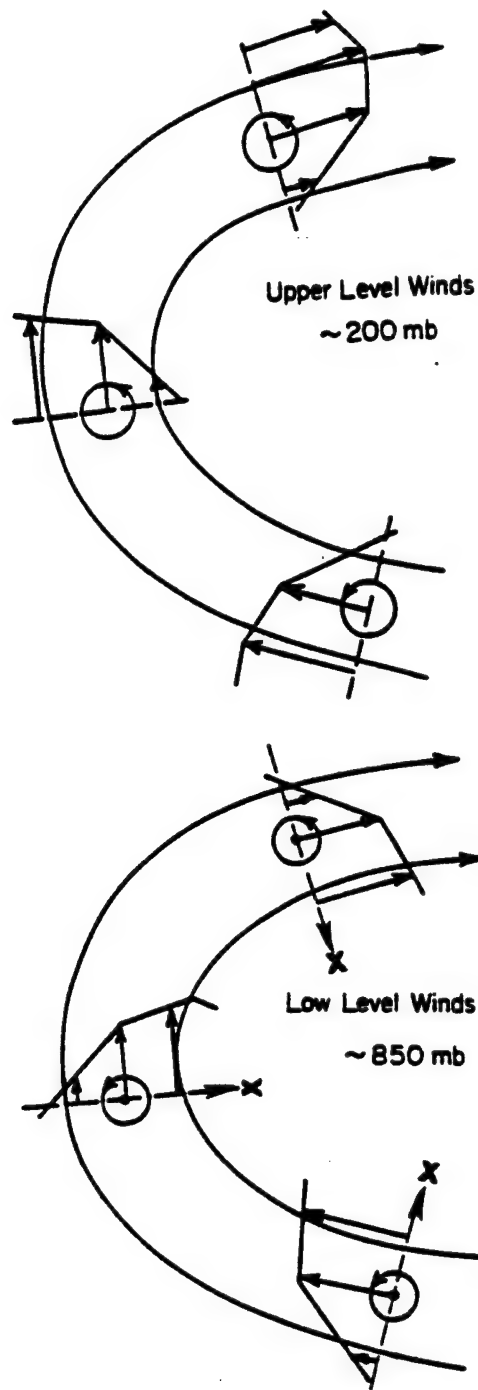


Figure 12: Idealized plan view representation of typical horizontal (or x direction) shear of the environmental parallel wind (V) across moving cyclones at upper and lower tropospheric levels. Note that $\frac{\partial^2 V}{\partial x^2}$ is negative at both levels for all direction categories.

Table 1: Rawinsonde measured average right minus left quadrant (MOTROT-VORT) wind or the wind of the environmental parallel to the direction of the moving cyclone center (m/s).

	Radius			
	3-5°	5-7°	7-9°	9-11°
200 mb	-3.0	-7.3	-10.4	-11.9
850 mb	2.0	1.5	1.5	1.7
$-\left[\frac{\partial^2 V}{\partial x^2}\right]_{200} + \frac{\partial^2 V}{\partial x^2} 850]$	5.0	8.8	11.9	13.6

MOTROT is the coordinate system where the vector of cyclone motion has been subtracted from all the wind and all the wind reports have been oriented with respect to the direction in which the cyclone moves. VORT refers to the mean vortex tangential winds. MOTROT-VORT means that mean vortex winds have been subtracted from all MOTROT winds. This representation gives the resultant environmental wind parallel and relative to the cyclone center.

of the direction of the 5-7° 850-300 mb deep layer mean wind. This generalized leftward motion of the cyclone's inner core region is hypothesized to be a natural consequence of the TC's faster inner-core forward propagation. This faster inner radius propagation causes a front to rear quadrant tangential wind asymmetry at inner radii relative to the front minus rear outer radius winds. This causes the inner vortex to move to the left of the outer vortex (Fig. 13).

It is also possible to interpret the leftward propagation in terms of the horizontal gradient of environmental relative vorticity. Note in Fig. 12 that there is higher environmental relative vorticity to the left than the right side of the cyclone at both lower and upper tropospheric levels. This environmental relative vorticity gradient to the left side might also be used as a complementary argument to explain leftward propagation. But realize that this right to left side gradient in relative vorticity is a result of the inherent deep layer environmental baroclinicity field in which the tropical cyclone is embedded and not a consequence of a horizontal vorticity gradient within a barotropic flow field. Leftward cyclone propagation is also seen to be a consequence of the baroclinic environment in which the cyclone exists.

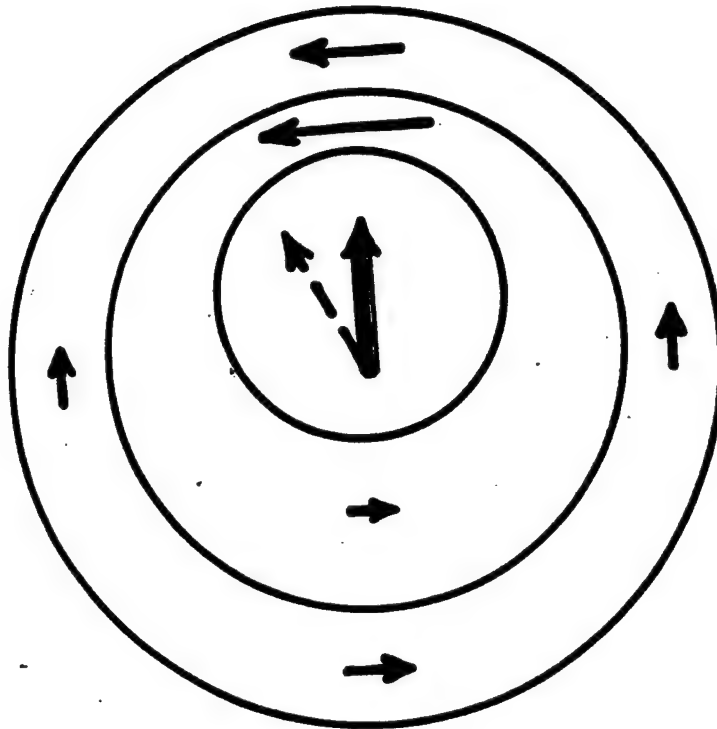


Figure 13: Illustration of how a factor westerly propagating central vortex will develop stronger front and weaker rear vortex tangential winds. These propagation induced front minus rear tangential wind asymmetries will cause the cyclone to also propagate to the left of the surrounding steering current.

6 BETA INFLUENCES

The latitudinal variation of the Coriolis parameter (or Beta) must have an important influence on the propagation of the tropical cyclones. Because of Beta, it is not possible to have a symmetric wind field or pressure field. Figure 14 portrays these two relationships in exaggerated form for Northern Hemisphere conditions and stationary cyclone conditions. The upper left diagram shows a symmetric wind field. Note the asymmetric isobars that would be required for gradient wind balance. It would be impossible for such a vortex to maintain a circular balance of its mass field. The lower left diagram, by contrast shows a symmetric pressure field with the higher low latitude tangential wind speeds which are necessary for a wind-pressure balance. Again, it is not possible for a circulation of this type to conserve its mass flow. It is likely that nature arrives at a compromise of these two idealized flow field extremes. This is represented in the right diagram. But again, a circular mass balance is not possible. As shown by the arrows of Fig. 15, it is required that there be an enhanced mass inflow on the west side of the cyclone and an enhanced mass outflow on the right side. Are there observed systematic and geographical oriented wind and convective asymmetries in real tropical cyclones?

Our rawinsonde composites document such an expected left side radial inflow and right side radial outflow. Figure 16 shows such motion (or MOT) subtracted inflow for our all west motion Atlantic composite. Note the consistent West to East cyclone relative wind flow through. This is typical of all our other direction and speed stratified composite analyses. Table 2 portrays average conditions for 1-11° radius mean inflow in Octant 3 (west side) and mean outflow (Octant 7) for our west moving West Pacific and Atlantic rawinsonde composites. Note the consistent left side inflow and right side outflow. Our northward and northeast flow stratifications show similar results.

This Beta induced radial inflow on the cyclone's left side and outflow on the right side causes an asymmetrical tangential wind field and (with some downwind advection) strongest tangential winds on the cyclone's southwest and south sides and weakest winds on the north and northeast sides. Figure 17 portrays these tangential wind asymmetries in a coordinate system with cyclone

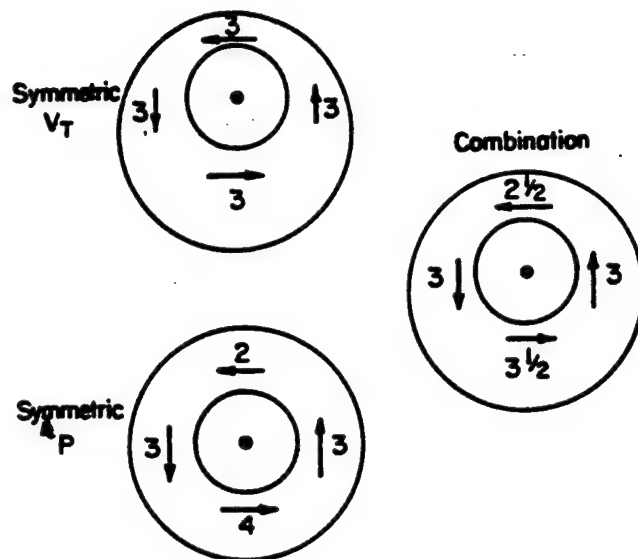


Figure 14: Idealized and exaggerated illustration of a stationary symmetric and balanced wind field (upper left diagram) where, due to Beta, isobars must be asymmetric. Numbers represent wind velocity. The contrasting diagram (lower left) shows a symmetric pressure field where wind-pressure balance and Beta considerations would dictate an asymmetric wind field. The diagram on the right represents a likely compromise between these two extreme states.

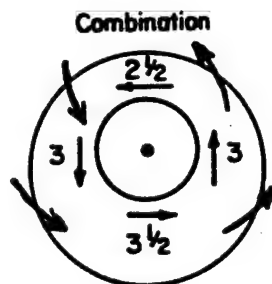


Figure 15: Likely wind flow response of a cyclone vortex attempting to obtain a wind-pressure balance in the presence of a North-South variation in Coriolis parameter (or Beta).

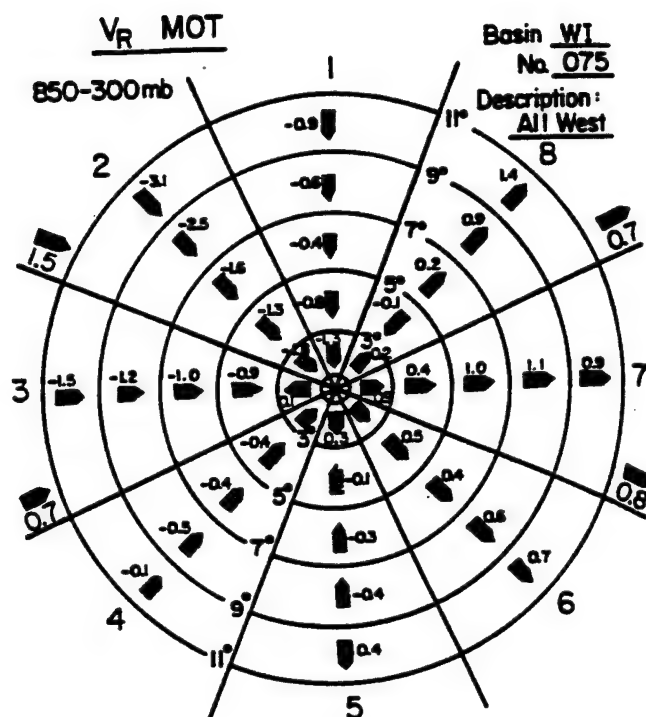
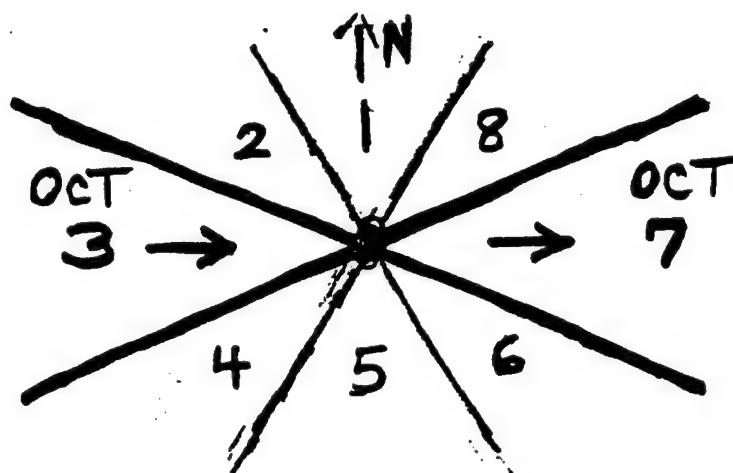


Figure 16: Plan view of a rawinsonde composite of radial winds in the 850-300 mb layer in the Motion (MOT) coordinate system for westward moving cyclones in the Western Atlantic. (In m/s).

Table 2: West Indies (WI) and Western Pacific (WP) westward moving tropical cyclone rawinsonde composites of 850-300 mb layer, 1-11° radius wind (V_R) in the west (Octant 3) and east (Octant 7) and the Octant 7 minus Octant 3 differences. Bottom (diagram) gives the geographic location of these octants relative to the cyclone center.

Stratification	West	East	Octant 7
	Octant 3	Octant 7	Minus Octant 3
WI 070 Slow West	-0.9	0	0.9
WI 071 Fast West	-1.5	1.2	2.7
WI 075 All West	-1.1	0.7	1.8
WI 077 Int. West	-1.0	0.7	1.7
WI 082 All SW	-0.7	1.2	1.9
WP 180 Slow West	-0.6	0.3	0.9
WP 181 Fast West	-1.0	1.4	2.4
WP 187 Int. West	-1.1	0.8	1.9
WP 192 All SW	-0.6	0.3	0.9
Average	-0.9	0.7	1.6



motion and the mean vortex flow subtracted out of each sounding (i.e., MOTROT minus VORT). Table 3 shows that all of our storm basin and direction of motion stratifications indicate that the 850-300 mb tangential wind asymmetries are strongest on the cyclone's south and southwest sides. Note the systematic positive tangential wind asymmetries on the cyclone's west and south sides and the negative tangential wind asymmetries on the north and northeast sides.

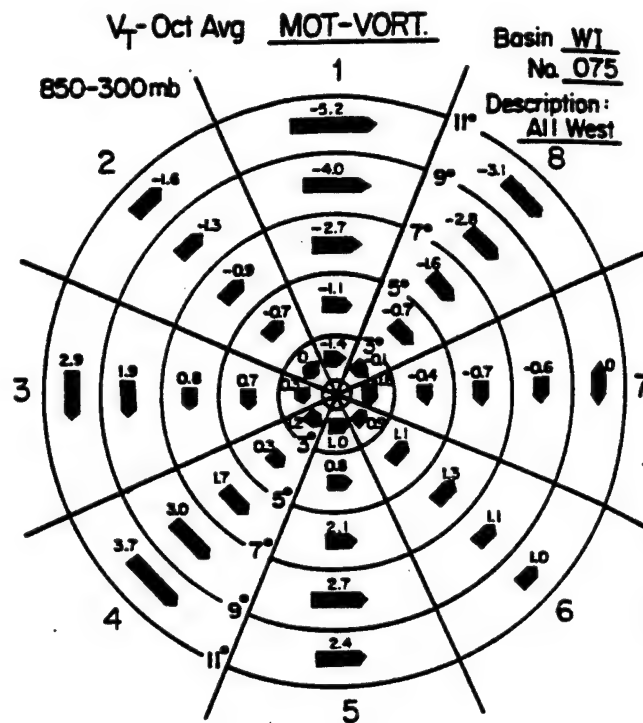


Figure 17: West Indies westward moving rawinsonde composite of the 850-300 mb tangential wind asymmetry in the Motion and Vortex subtracted (MOT-VORT) coordinate system. Values in m/s.

Such Beta induced geographic radial and tangential asymmetries would be expected to cause similar azimuthal asymmetries in the cyclone's deep convection. One should expect more deep convection to occur to the west and south sides of the cyclone and less convection to occur on the east and north quadrants; and, this is what occurs. Figure 18, from Hallin's (1991) analysis of the area coverage of cold infrared (IR) cloud temperatures for West Pacific tropical cyclone composites

Table 3: West Indies (WI) and Western Pacific (WP) rawinsonde composites of the 850-300 mb tangential wind asymmetries at 9-11° radius in the Motion and Vortex subtracted coordinate system (MOT-VORT) for North and Northeast moving cyclones (top table) and for westward moving cyclones (bottom table). Values in m/s.

Stratification	Northeast Oct. 1-8-7	Southwest Oct. 3-4-5	Oct. 3-4-5 Minus Oct. 1-8-7
WI 072 Slow North	-2.5	3.0	5.5
WI 073 Fast North	-5.3	5.7	11.0
WI 076 All North	-3.5	4.2	7.7
WI 078 Int. North	-3.6	4.7	8.3
WI 079 All NE	-3.0	3.3	6.3
WI 080 Fast NE	-2.8	3.3	6.1
WI 081 Slow NE	-2.7	3.2	5.9
WP 182 Slow North	-1.9	2.8	4.7
WP 183 Fast North	-4.7	6.0	10.7
WP 188 Int. North	-3.2	4.1	7.3
WP 189 All NE	-1.6	2.4	4.0
WP 190 Fast NE	-2.7	3.3	6.0
WP 191 Slow East	-1.1	2.1	3.2
Average	-3.0	3.7	6.7

Stratification	North Oct. 2-1-8	South Oct. 4-5-6	Oct. 4-5-6 Minus Oct. 2-1-8
WI 070 Slow West	-2.8	1.6	4.4
WI 071 Fast West	-4.2	3.7	7.9
WI 074 No Motion	-2.1	0.5	2.6
WI 075 All West	-3.3	2.4	5.7
WI 077 Int. West	-3.2	2.2	5.4
WI 082 All SW	-4.4	3.5	7.9
WI 090 1005-990 mb	-3.0	2.1	5.1
WI 092 SLP < 965 mb	-3.7	2.8	6.5
WP 180 Slow West	-3.9	3.2	7.1
WP 181 Fast West	-5.8	5.6	11.4
WP 184 No Motion	-2.9	2.1	5.0
WP 187 Int. West	-5.3	4.6	9.9
WP 192 All SW	-4.5	3.8	8.3
WP 200 980-1000 mb	-4.4	4.0	8.4
WP 202 SL < 955 mb	-6.1	5.4	11.5
Average	-3.8	3.1	6.9

shows large amounts of asymmetric deep convection differences. Note that at radii between 2-4°, the area of cold IR cloud temperatures (which is assumed to represent the amount of deep convection present) is observed to be 28 and 35 percent higher on the west and south quadrants and 28 and 35 percent lower in the north and east quadrants. This is no observation anomaly. It is to be expected that such Beta induced convergence in the cyclone's left quadrant and divergence in the right quadrant should cause an east quadrant enhancement of convection and a west quadrant suppression. It is also to be expected that once west side deep convection is initiated, this convection should maintain itself from down-draft generation of new convective elements and their downwind tangential advection. Convection should also be expected to be enhanced to the cyclone's south side. By similar reasoning, down-draft generation and advection would lead to convection suppression in the cyclone's north quadrant. Such azimuthal deep convective asymmetries are hypothesized to be primarily a consequence of Beta influences.

These azimuthal convective asymmetries should be expected to generate deep layer asymmetries in outer radius vorticity fields and thus, in the cyclone's propagation. Modeling evidence supporting the likely influence of azimuthal convective asymmetry is given in Flatau's (1991) numerical experiments of 72-hour cyclone propagation in a no steering environment, containing a north-south variation of the Coriolis parameter and, with and without conditions of azimuthal convective asymmetry to the south. Her results are shown in Fig. 19. Curve S in the top diagram shows the 72-hour track movement resulting from pure-Beta propagation with no convection asymmetry. Curve AS1 shows the same track propagation but with a combination of Beta and azimuthal convective asymmetry such that higher amounts of convection are imposed to the cyclone's south side, and lower amounts of convection to the north (lower left diagram). Note how much the track deviates to the south from the pure Beta propagation track. An even larger deviation from pure Beta propagation occurs in curve AS2 wherein the highest amounts convection are placed to the southwest and the low amounts of deep convection to the northeast (conditions of the lower right diagram).

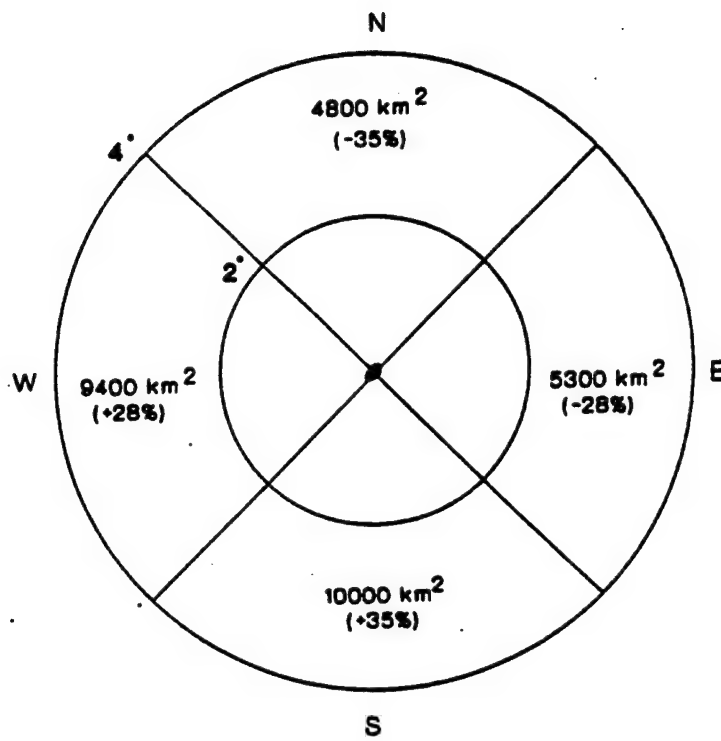


Figure 18: Average area of deep convection with cloud tops colder than -75°C in each quadrant at 2-4° radius. The quadrant deviation from the symmetric area is shown in parentheses. (From Hallin, 1991).

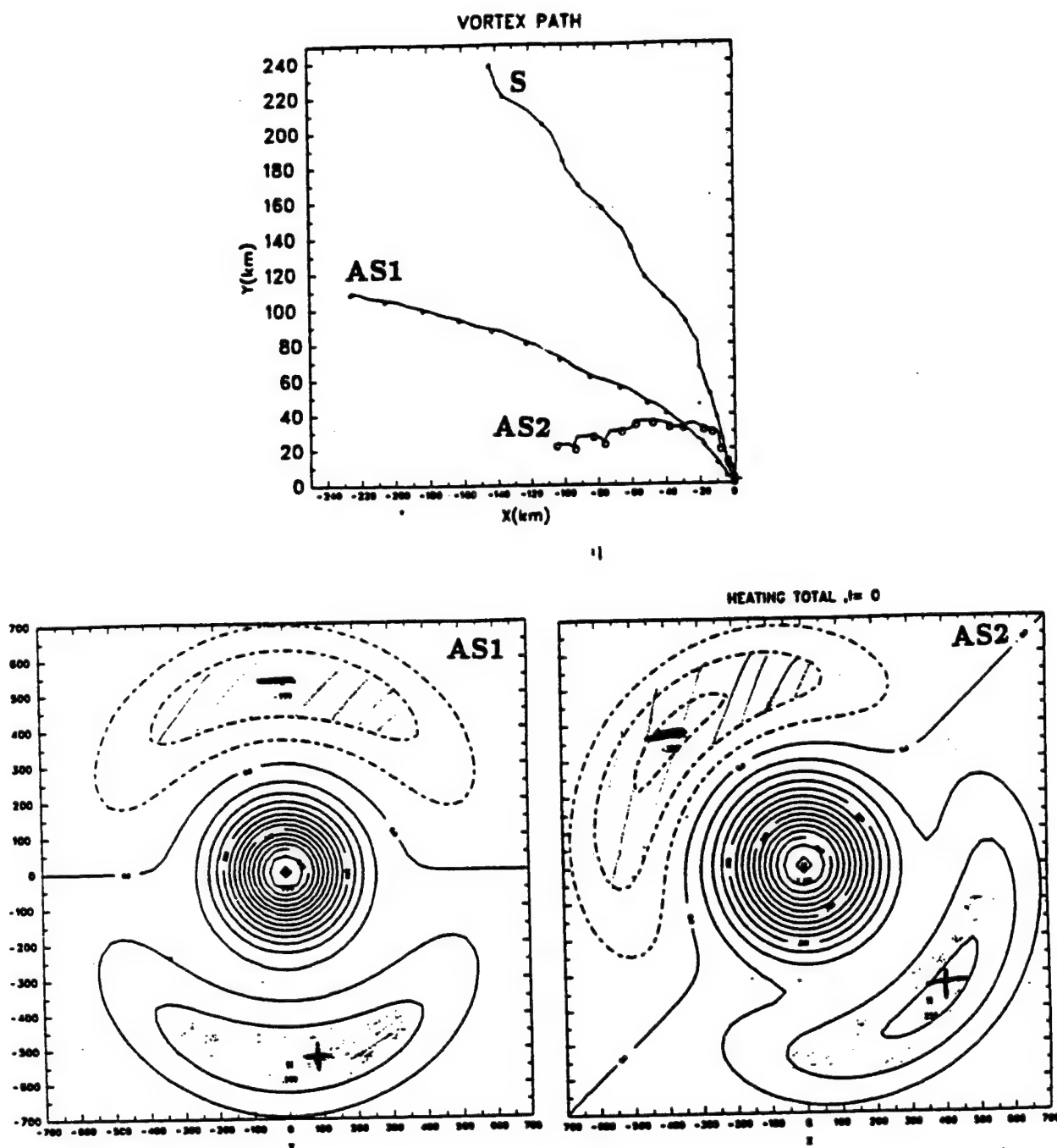


Figure 19: Flatau's (1991) 72-hour tropical cyclone no-steering-flow track propagation resulting from pure barotropic Beta influence (curve S), from Beta and asymmetric heating with maximum heating to the south (curve AS1) and from Beta when asymmetric heating is placed to the southeast (curve AS2).

It appears that the Beta influence on tropical cyclones is such that it causes an asymmetric rearrangement of wind and deep convection within the cyclone wherein maximum tangential wind and maximum deep convection is established on the cyclone's southwest side. These wind and convective asymmetries act to cancel a sizable amount of the northwesterly cyclone drift during pure barotropic model Beta propagation. Thus, in retrospect, we should not have expected that real world tropical cyclones would show such a simplified northwesterly track propagation as the barotropic models have so consistently indicated. This helps explain why the expected variations in northwest barotropic model propagation alterations and strength of outer circulation propagation differences are not well verified in our rawinsonde stratifications. Our observations indicate that all tropical cyclones, irrespective of direction, speed, and other wind strength, pretty much have the same amount of faster forward speed propagation and 10-20° left world propagation relative to their respective 5-7° radius and 850-300 mb surrounding flow patterns. The real world influences of Beta are thus viewed to be more complicated than those perceived by the simple barotropic propagation.

The fact that the real world environmental baroclinic propagation influences (as just discussed) are very similar to the expected propagation influences of the simplified barotropic Beta model results have given false confidence to the interpretation of the barotropic propagation results. It has been too easy to accept the simplified barotropic propagation results as approximating nature when, in fact, such propagation was not a direct result of pure one level Beta, but rather a consequence of the existence of the tropical cyclone in a special environmental baroclinic field. The complicated real world effects of Beta may largely cancel themselves. Real world propagation appears to result from other physical considerations.

7 SUMMARY

Our special cyclone motion related rawinsonde composite analyses propose a new method of explaining tropical cyclone propagation. Tropical cyclone propagation is primarily a result

of the tropical cyclone's existence within a special baroclinic environment with an upward and leftward sloping subtropical ridge to its right side and an upward and leftward sloping monsoonal trough or frontal system to its left. This baroclinic environmental flow is such as to cause deep layer "baroclinic-gyres" similar to the type of single level gyres developed in barotropic motion simulations.

Tropical cyclones typically move in a clockwise manner (in the Northern Hemisphere) around a warm subtropical high pressure system on their right side. A relatively cool monsoon trough or frontal system is almost always present on the tropical cyclone's left side. The resulting deep layer environmental left side (cool) to right side (warm) horizontal temperature gradient across the cyclone introduces a vertical right to left upward slope of the cyclone's surrounding environmental anticyclone, monsoonal trough, and frontal flow features. It is this leftward slope to cold air which develops wind conditions in the sense so as to cause the observed TC propagation.

The leftward propagation of the tropical cyclone is a consequence of the forward cyclone propagation which causes the establishment of front minus rear tangential wind asymmetries at inner radii which are stronger than at outer radii. These front minus back wind asymmetries induce a leftward motion to the inner-core vortex relative to its outer radius flow. This leftward propagation might also be thought of as a result of the higher environmental vorticity on the left side of the cyclone vortex.

As most forward and leftward TC propagation measurements have been made on cyclones moving in a westerly or northerly direction, it has been appealing to interpret such propagation measures as a consequence of the northwesterly Beta-drift inherent in one layer modeling results. But these barotropic Beta-drift propagation interpretations appear not to be a close analog of real-world tropical cyclones. Barotropic modeling has overly exaggerated the one-level Beta-drift influence on cyclone propagation. This is because barotropic modeling has not included the deep layer baroclinic environmental influences in which real cyclones are embedded and influenced by. Such baroclinic environmental influences appear to be a fundamental ingredient of cyclone forward

and leftward propagation. Tropical cyclones continuously adjust to their Beta environment through development of North-South tangential wind asymmetry and enhanced deep convective asymmetry. Barotropic simulations lack such real-world cyclone western and southern quadrant wind and convective asymmetries that act to adjust and largely counter balance much of the pure Beta drift from the barotropic simulations.

8 ACKNOWLEDGEMENT

This research has been funded by the Office of Naval Research Marine Meteorology Division. I am grateful for the encouragement and support I have received from Robert Abbey and Russell Elsberry. The author is also indebted to William Thorson and Todd Massey for their expert computer assistance and Sheila Long for graphical assistance.

9 REFERENCES

- Carr, L. E., 1989: Barotropic vortex adjustment and propagation in response to asymmetric forcing with application to tropical cyclones. Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA.
- Carr, L. and R. L. Elsberry, 1989: Observation evidence for beta-induced tropical cyclone motion relative to steering. Submitted to *Mon. Wea. Rev.*
- Chan, J. C. and R. T. Williams, 1987: Analytical and numerical studies of the Beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, 44, 1257-1265.
- Chan, J. C. and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, 110, 1354-1374.
- DeMaria, M., 1985: Tropical cyclone motion in a nondivergent barotropic model. *Mon. Wea. Rev.*, 113, 1199-1210.
- DeMaria, M., 1987: Tropical cyclone track prediction with a barotropic spectral model. *Mon. Wea. Rev.*, 115, 2346-2357.
- Evan, J. L., et al., 1990: Interactions between a barotropic vortex and an idealized subtropical ridge-I: Vortex motion. *J. Atmos. Sci.* in press.
- Flatau, M., 1992: The role of baroclinic processes in tropical cyclone motion. Dept. of Atmos. Sci. Paper No. 488, Colo. State Univ., Ft. Collins, CO, 140 pp.

- Fiorino, M. and R. Elsberry, 1989: The role of vortex structure in tropical cyclone motion. *J. Atmos. Sci.*, 46, 975-990.
- Gray, W. M., *et al.*, 1988: Tropical cyclone motion research—observations and physical implications. Report written for Rainbow Beach, Australia ONR sponsored workshop, 121 pp. plus 87 pages of Appendices.
- Gray, W. M., 1991: Tropical cyclone propagation. Preprints, 19th AMS Conference on Hurricanes and Tropical Meteorology, May 6-10, Miami, FL, 385-390.
- Hallin, S. C., 1991: Diurnal variations in tropical cyclones. Preprints, 19th AMS Conference on Hurricanes and Tropical Meteorology, May 6-10, Miami, FL, 416-421.
- Holland, G. J., 1983: Tropical cyclone motion: Environmental interaction plus a beta effect. *J. Atmos. Sci.*, 40, 328-342.
- Smith, R. K., 1989: An analytical study of tropical cyclone motion using a barotropic model. Submitted to *J. Atmos. Sci.*
- Willoughby, H. E., 1988: Linear motion of a shallow-water, barotropic vortex. *J. Atmos. Sci.*, 45, 1906-1938.

10 APPENDIX

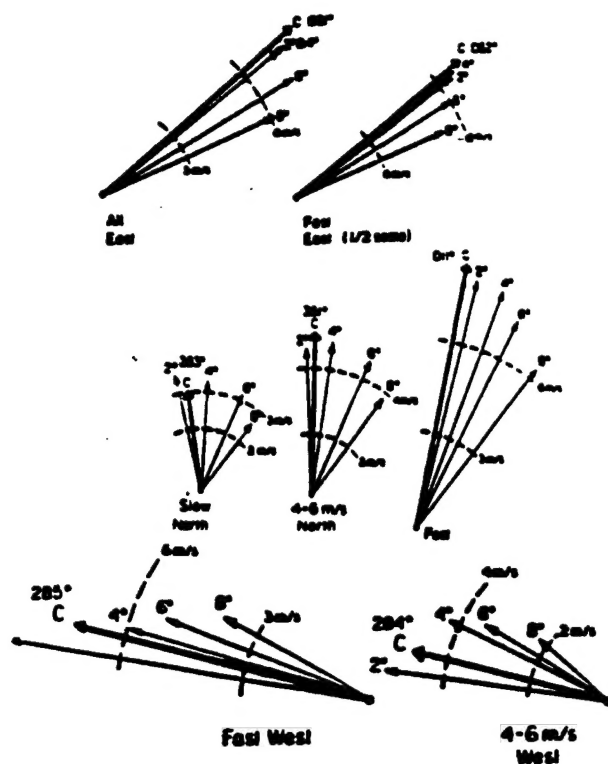


Figure A1: Layer average (850-300 mb) symmetric wind vectors in various radial bands relative to the mean cyclone motion (C). Stratifications are by cyclone speed for NW Pacific northeasterly (top), northward (middle) and westerly moving cyclones. 2° is 1-3° mean radial motion, 4° is 3-5° mean motion, etc.

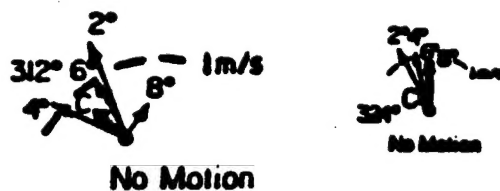


Figure A2: Stratification of 850-300 mb mean winds for cyclones with speeds of 3 m/s or less (cyclone vector is C) in the NW Pacific (left) and the West Atlantic (right). There is no obvious northwest draft of C relative to the outer radius winds.